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Systems Design Analysis Applied to Launch Vehicle Configuration

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TECHNICAL PAPER

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I. INTRODUCTION

As emphasis in the aerospace industry shifts from optimum performance to low life-cycle cost, the rate of major technological design advancement is giving way to design management improvements. Common to these evolving improvements are the principles and tools of total quality management (TQM). This study reviews the systems engineering methodology as it applies to engineering design analyses, and identifies TQM applications to provide high reliability, low-cost aerospace designs. Since designing to high reliability can be correlated to reducing long-term cost of failures and spares, cost emerges as the systems common denominator.

The seriousness of program cost control is reflected by current NASA policy[1] to critically reconsider active projects having excessive cost overruns. The source and acute control of costs are embedded in the design process, thus designers and discipline teams must successively explore and adapt the latest quality and cost-saving techniques developed and practiced by commercial industries. Many of these quality techniques are addressed by systems design analysis.

Clearly, this is not another document on project or systems engineering management,[2] nor on standard design practices. It is, however, an analyst's approach to a total life-cycle systems design which is initiated by firm user requirements and progresses down to component design for low cost manufacturing and operations through the three-phase systems-analysis process. Each hierarchic decomposition generates new design tasks in which TQM provides rigorous techniques for defining requirements, developing solution options, and developing selection criteria. TQM is further applied to integrate the decomposed elements into systems producing quality design in performance, manufacturing, verification, and operations. This approach avoids the breakdown experienced in prior approaches when systems were decomposed, designed, and synthesized. The resulting technical processes are bounded by customer satisfaction on the one side and affordable cost on the other. Success of integration and critical issues recognition rests with the technical leadership.

Though the total systems method is generally applicable to most complicated systems, this presentation is made more useful by directing the process on a very large and familiar system, a launch vehicle configuration. No attempt is made to cover conventional aspects of systems design, nor to elaborate on suggested processes, techniques, and standards referenced here and amply documented elsewhere. The scope and depth of this presentation are limited to delineating techniques that might enhance systems design concepts leading to affordable projects.

II. DESIGN PREMISE

Design is conceived of a demand for a product that performs a need easily, reliably, and affordably. From this concise premise, the design processes and analytical techniques evolve which

translate demands into engineering requirements and solutions. Processes and techniques provide design thoroughness, and cost enforces design balance. While requirements and solutions are clearly balanced and controlled by finite budgets, the balance between customer needs and solutions is more formidable, particularly between solutions. Balance and thoroughness are the hallmarks of a successfully designed product.

Given a set of payload requirements, a balanced and thoroughly designed launch vehicle is rooted in the integration of user expectations, performance, manufacturing, verification, and operations roles. Reliability and cost are quantifiable design controls that cut across all roles and within a role. Reliability enforces margins and redundancies into functional designs according to criticality of a component's flight performance, manufacturing reject rates, quality check sneaks, and operational preparations and holds. Cost and role-user expectations guide the scope and level of technology to be applied in each role.

Operations is a recurring cost, and operations and its associated facilities have been the most underestimated role. Operations must be addressed up front along with propulsion selection, and must be critically induced in all design trades of systems through components and roles to reduce labor, human errors, preparation checks, and processing. Technology costs on first stage performance should be less than upper stages. Technology costs on recurring manufacturing and operations of expendable vehicles should be considerably less than the limited manufacturing and the recurring launch, recovery, and refurbishment of reusable vehicles.

Design processes and techniques insure thoroughness of product, and are the substance of this paper, but design thoroughness is only as good as the competence of the technical leadership staff and design analysts. Design processes are performed under systems engineering and systems design analysis methods, and design techniques are accessed from standard practices and TQM. Processes, techniques, and leadership must commit complete assessment of interactions of decomposed systems, elements, etc. by all roles and disciplines to identify design issues and imbalances. Leadership further assures that finally designed components are orderly integrated into elements and systems, perform as intended, and are provided with appropriate operational simulations and checks. But leadership is a "potluck" situation. If the king is weak and the counts are strong, or vice-versa, team respect and confidence may better affirm design success than if the king and the counts are weak.

III. QUALITY SYSTEMS APPROACH

Systems management, systems design, and other systems approaches are well-established processes in the aerospace communities for developing all or any part of large, complex systems (fig. 1). The systems design process provides an orderly transformation of mission objectives into a detailed systems design through three continuous and correlated phases; concept, definition, and design. These systems phases have advanced the design practice from an earlier single option procedure to development of multiple options for trading and selecting optimum performances of mission systems.

In the current environment of budget constraints and potential competition, and in response to a maturing industry, the systems process is now extended to emphasize customer needs, reliability, and low life-cycle cost. Techniques to accomplish these are being continuously developed and
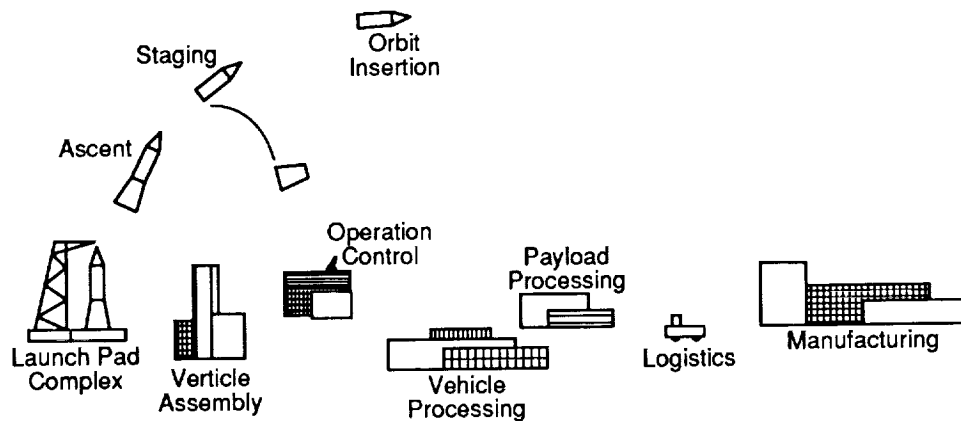
Figure 1. Aerospace mission systems.

improved by a variety of global industries under the practices of TQM, continuous improvement (CI), etc. Just as the systems process (fig. 2) prevailed over the old single design option to multiple design options and trades, TQM penetrates design options further to select combinations of parts, materials, manufacturing, and operation alternatives that improve product quality and user satisfaction at lowest total cost.
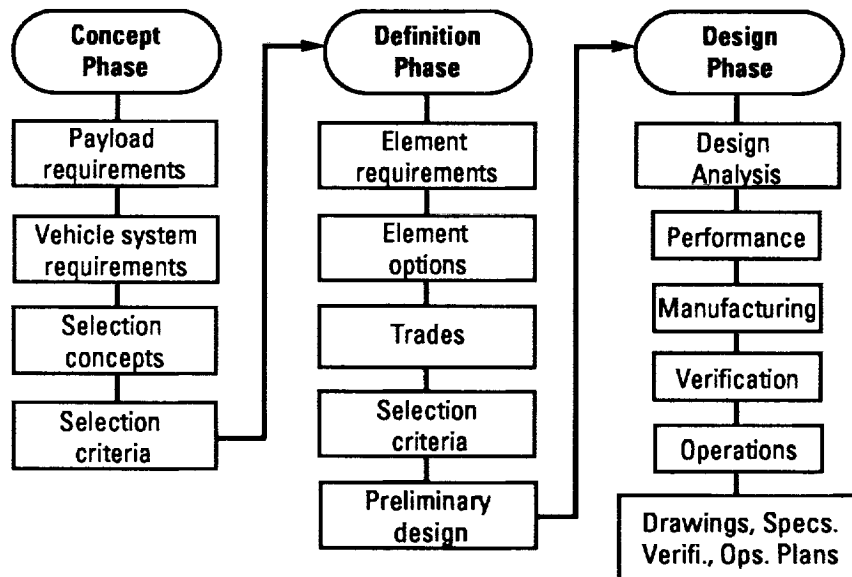
Figure 2. Systems design process.

A total system decomposes into tiers of systems, elements, and components throughout the concept, definition, and design phases. Each tier decomposes further into design parameter tasks which expand and interact with systems, elements, or components of the respective tier. Tasks identify design parameter requirements, develop design options to satisfy requirements, perform trades, and formulate criteria to select the best option leading to final design, specifications, and plans of systems, elements, and components. The prime objective of this study was to learn where and how, within a tiered process, the established TQM techniques may be adapted to a vehicle configuration analysis, and to recognize that the same techniques may be extended to all of the vehicle systems, elements, and components.

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A. Matrix Methods

A system is a set of parts whose behavior depends on the behavior of other parts. The need to flow scheduled information in a complex system often results in decisions based on limited analyses and understanding of user requirements and their complex relationship among interacting systems. A variety of matrix methods are introduced to make these relationships more orderly, visible, and understandable, and many others are extensively applied in referenced TQM techniques.

The system, or progression, of matrices may initiate the design process with a user matrix having a wide spectrum of "what" and "how much" requirements. The "what" parameters are more conveniently listed in rows, and the "how much" requirements are noted in columns such that each column represents a congruent package. This type matrix provides the visibility and facility to compare, rearrange, and consolidate requirements across the columns, and to resize and reduce the number of packages. Columns of competitors' accommodations may be included for marketing strategy.

In applying the matrix progression of figure 3 to a delivery system, a payload requirements matrix (a) is developed with rows of user requirements packaged in columns according to common services, sizes, and launch and ascent constraints. It is a pseudomatrix in that requirements within each column interact but are independent of other columns.
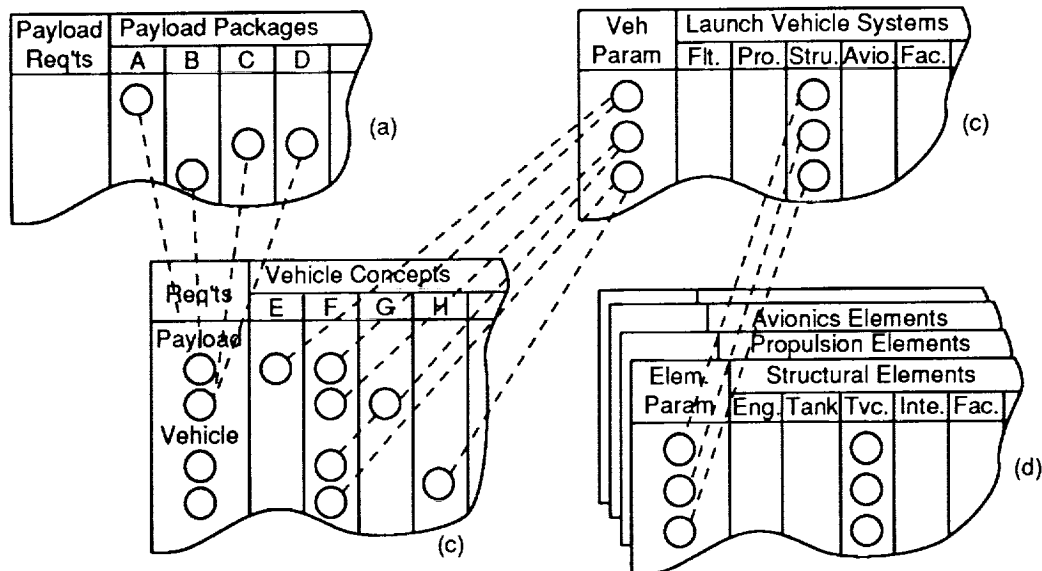
Figure 3. Matrix progression.

Payload matrix (a) progresses to another pseudomatrix (b) for developing vehicle concepts to deliver the total set of payload packages. Matrix (b) rows consist of select payload requirements driving vehicle parameters and basic conceptual vehicle parameters. Vehicle design parameters include propellant systems characteristics, staging schemes, mass ratios, and natural and induced environments. Matrix (b) provides the format for varying and combining vehicle parameters and payload requirements to generate a host of vehicle concepts characterized by specific parameters integrated in each column. Each column represents an independent or evolutionary vehicle concept, and only parameters along the columns interact.

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Another type matrix is a systems matrix, and it is analogous to developing sets of simultaneous equations in which variables within each equation interact with variables of other equations within the set. It is applicable to vehicle systems where vehicle design parameters of a specific concept in matrix (b) seed a third matrix (c) to interact with vehicle systems across each row, including ground facilities, and along each column. Parameters along each column interact in different orders in different columns. Each interacting parameter represents a design task which suggests design requirements and solutions. A design task is accomplished through the information of previously accomplished tasks. *When parameters must be estimated to initiate a design feedback loop, those parameters create sources of iterations across the systems,* and matrix progression is one means of tracking its interaction, iterations, and convergence. As solutions introduce more systems parameters and generate more detailed systems information, matrices of interacting estimated requirements and solutions are iteratively resolved and integrated into congruent systems.

Parameters from a developed systems matrix may be selected to initiate a lower tier matrix of parameters. Matrices may progress to any level of elements, components, and parts. Each vehicle element defined by each column in matrix (c) may be further decomposed into vehicle element parameters interacting with element component parameters to establish another systems matrix (d). Again, element parameters from a systems type matrix interact across each row with subelements and components, but interact in different orders along different columns according to information flow.

Crucial to an efficiently managed system is the ability to decompose and rearrange a complex matrix scheme such as to more rapidly flow all sensitive interacting information and to provide more time to produce a coherent design in a more systematic way. As a system is decomposed along columns, the behavior of smaller parts becomes easier to analyze, but their relationship with other parts becomes more complex, and the whole system becomes more difficult to solve. Steward[3] developed a method for analyzing and managing the interaction of parts and the information flow in a system. The decomposed tasks are listed and numbered in the order they might be completed before the next task may begin. Predecessors of each task are listed in two adjacent columns. In one column are the sensitive predecessors whose estimated errors cause large effects on the tasks that follow, and the second column lists insensitive predecessors. This same information is charted into a precedence matrix with rows and columns numbered by tasks. Tasks are then reordered in the sequence in which they are to be done through a procedure of partitioning and tiering which may be computerized. The matrix may also develop into change control and verification tools.

Figure 3 matrices provide the visibility of design tasks to be done during each design phase, and their interaction with systems across the rows. Steward's matrices provide the strategy for accomplishing the tasks, and assert an item hierarchy, interrelation, and feedback with other items. Narratives based on engineering analyses define the why, how, and magnitude of their interaction. Narratives address requirements, solution options, cost analyses, operations scenarios, and criteria for selection. Both matrices and narratives are used to describe total system requirements and solutions.

B. Quality Techniques

Quality techniques most applicable to systems design phases are quality leverage, concurrent engineering, Pareto's principle, and quality through robustness and function deployment. Final analyses must be complete and based on rigorous examination of accurate data. Incorrect collection of data and incomplete analysis of it lead to precarious conclusions. Obviously, diligent application of

TQM methods will require new and improved analytical skills and tools, and will often increase design effort up front, but should ultimately accomplish all project objectives in a shorter time and at lower total cost.

In the scale of quality leverage,[4] the earlier the control of objectives, the more timely and efficient are the solutions and modifications (fig. 4). The better and more complete the concept options, the more effective and successful are the subsequent concept selections and developments. An overlooked superior option or a poorly selected concept usually engages costly advanced technologies, materials, and manufacturing approaches to just comply with specified performance. Quality leverage principle is proven to be cost saving though it is certain to stretch early design phases and invite charges of "analyzing to death" and "delaying getting on with the job."
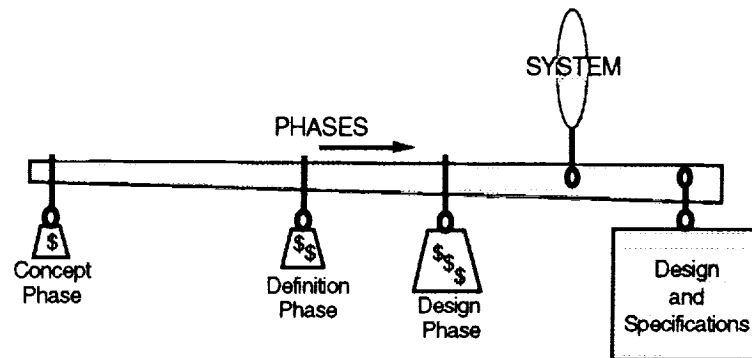

Figure 4. Design quality leverage.

Concurrent or simultaneous engineering is a team effort representing all essential disciplines involved in the analysis and selection of concepts, components, materials, manufacturing, processes, and major operations. It is the focus and integration of related physics, applicable knowledge, and experiences inherent in a large mixed team effort. While concepts are generated by individuals, best selection and enhancement are accomplished by concurrent engineering teams. Concurrent engineering is initiated during the concept phase and may expand and branch into systems and element integration working groups as required during design phases. Team success depends on its technical leadership and experiences.

Pareto's principle observes that 20 percent of parameters cause 80 percent of results. A reasonable approach for setting priorities to improve products or resolve problems is to first address the top 20 percent of the most significant parameters. These parameters are identified through histograms of their relative sensitivities to goals, e.g., ideal performance and lowest cost. The principle may also help specify hierarchic reliabilities.

Providing product quality for the user translates into designing a system that is easy to use, works well, is safe, is durable, and performs these user requirements with a minimum variability. A system that is designed and produced to minimize deviations caused by noise factors (external environment, unit-to-unit variations, and deterioration) from ideal performance is a robust design. Launch pad delays and frequent maintenance are usually associated with poor robust systems. The robust design method[5] improves quality and productivity of a product at low cost through concept design, parameter analysis, and tolerance design. The ideal engineering performances of the selected concept are simulated and used in the analysis of reducing sensitivity-to-noise factors and manufacturing costs. In parameter design, the best combination of control factors (design parameters that do

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not affect manufacturing cost) to minimize quality loss is determined using wide tolerances and low-grade components and materials. Techniques used are signal-to-noise ratio to measure quality and orthogonal arrays to assess multiple design parameters simultaneously. If the quality loss is off-target following parameters selection, tolerance design is used to tradeoff loss due to variations in performance with cost of tighter manufacturing tolerance and higher grade materials and components (design parameters that do affect manufacturing cost).

Quality function deployment (QFD) is a highly disciplined team effort which converts general user requirements into explicit design requirements, and proceeds to develop details on "how" to satisfy them in matrix form. The next level of details produced is "how much" each design requirement is to be satisfied, which is balanced with cost. The method progresses through manufacturing operations and production requirements, and incorporates their measurable characteristics into detailed designs and specifications as shown in figure 5. All iterations and resulting modifications accomplished in the process are inexpensive paper changes made up front.
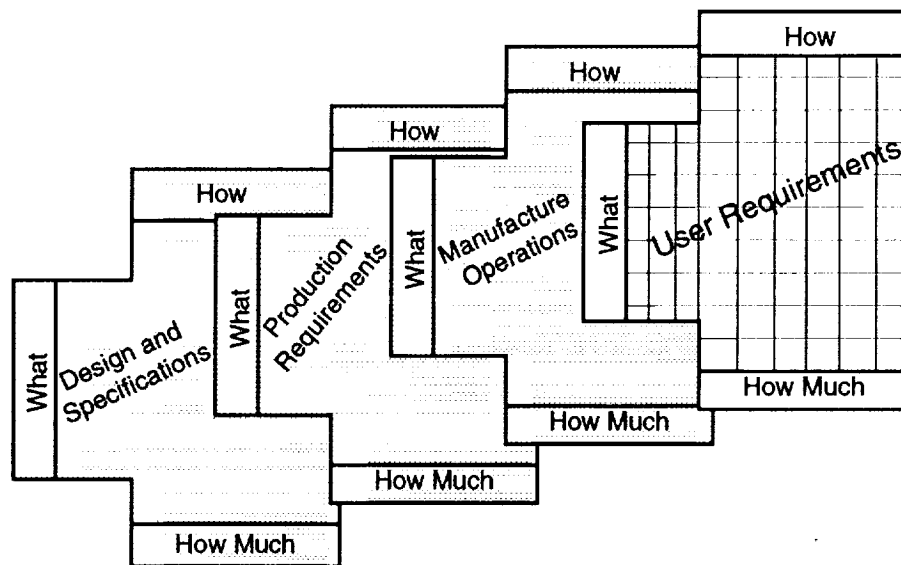
Figure 5. QFD process.

Another meaningful contribution to systems design is tailoring specified handbooks and referenced documents by selecting only requirements unique to the project and absent of prescribed solutions. Requirements and specifications should be accessed and controlled through a central electronic system. This practice has already been implemented between project customer and awarded contractors with significant savings in labor and logistics. It should be even more effective if unique requirement selections are computerized before requesting contractor proposals. Too often standard documents are "thrown over the fence" to contractors to legalistically interpret and discriminate their applicability, which results in undue protectionist conservatism. Total handbooks are sometimes specified when only a few paragraphs are relevant to the project, and worse, embodied sections that specify procedures contrary to other specified documents are overlooked.

In essence, the total systems approach and its matrices are initiated in the concept phase, with payload concepts and extend through vehicle concept, systems, and elements. They provide an orderly transformation of mission objectives into system and elements requirements leading to the definition phase. Requirements are legally binding[6] and are the basis for managing performance,

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reliability, schedules, and costs. TQM methods are invoked to generate quality requirements at minimum cost. The balance between legal requirements and the creativity emanating from TQM to provide high performance, low cost products is the challenge of the system analysis process.

C. Life-Cycle Cost

While user requirements and their accommodations represent one side of the balance, cost to implement them represents the other weighing pan. Judging from past projects, cost goals have not been achieved too well by the space industry. A major overrun cause is stretching the program to match fiscal appropriations. But aside from programmatics, designers have a unique responsibility to minimize overruns by completing design analyses at each design phase, controlling requirements buildup through all design phases, and reducing sources of engineering bottlenecks. The cheapest design changes are early paper changes.

Cost models are based on a variety of historical cost factors.[7] Weight is a design parameter routinely calculated and available for most tiers of assemblies and systems. Weight may be correlated to size and performance and is the most often used parameter to estimate cost. Thrust, power, and flow rates also characterize size and performance of specific systems which may be related to systems cost. Cost varies inversely with production quantities. Complexities directly increase cost. Advancing state-of-the-art increases the costs of learning new phenomena, potential bottlenecking, and new facilities. Cost models change with time because of inflation and technology improvements, and should be scaled accordingly.

Cost factors are difficult to quantify in the earliest phase, but become increasingly more definable with each subsequent phase. Though cost estimates based on system similarity are often sufficient for a concept phase, there should be no reluctance to analyze critical cost factors in an off-line definition phase type of details during the concept phase. Costing in the design phase is often initiated at the lowest component level and accrued to the assembled level. Operational costs over the life of a launch system are significant recurring expenses. The most representative operational data available are founded on the current space transportation system (STS). This limited statistical data base is a weakness which should be augmented in costing hardware through all systems phases. Cost of management and contingencies are included as a percentage of total project cost.

While engineering disciplines in concurrent engineering teams may not be skilled in estimating costs, many are experienced in evaluating development and production relative costs of one component, system, or concept over another. They may help modify cost models for increased complexity and technology development.

Cost models are the mechanisms for assessing trades and for tracking and controlling requirements buildup. They are initiated in the concept phase and expanded through all phases and levels of solutions. Models should provide the basis for identifying cost driving requirements (Pareto's principle) and sensitivities in support of exploring innovative methods and concepts for reducing cost or for assessing vehicle evolution requirements. They should provide the source and basis for making initial high leverage cost decisions and for setting development priorities on critical tasks. Cost models should serve to formulate budget controls, detect cost overruns, and pace efforts relative to prevailing funds. Good cost estimates throughout the systems design analysis are the balance and enforcers of successful projects.

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IV. CONCEPT PHASE

The concept phase is a first-order activity having the greatest quality leverage and, perhaps, is the most critical for the success of the mission. It is first and foremost a marketing phase which analyzes promising demands and competition for access to and for operation in space. It identifies a potential class of user needs, and it scopes missions within doable schedules and costs. Results of this phase are a set of select, top-level design specifications of customer needs and mission concepts to satisfy them. It should include a comprehensive set of mission requirements and constraints; first-order definition of vehicle configuration, systems, and elements; operation scenarios; and a basis for estimating costs. Subsequent phases peel the systems and elements to lower hierarchies, and expand the systems process of requirements, solutions, and selections using TQM .

Incomplete marketing and technology analyses must be included among the root causes of failed initial concepts. Examples of past inadequate concept phases are *Apollo* dual launches to Earth-orbital rendezvous, fly-back shuttle booster, solid rocket motor composite cases, and eight-man Space Station *Freedom*. These concepts were passed onto the definition phase and modified there, representing major changes, patch-ups, and recycling of the concept phase at substantial schedule slippages and costs.

A. Marketing Objectives

Payloads are usually established about specific Earth-orbital services or deep space probe experiments. A crew or cargo transfer vehicle may be included among special payloads. Their development periods are usually less than 10 years, and a common objective is to make them affordable.[8] Large payloads may cost less per pound if delivered by standard launch vehicles and if payloads are allowed more margins. Payloads should be expected to grow 10 to 15 percent during development. Low-cost, common-carrier, and payload-growth margins are basic clues for selecting launch vehicle objectives, but developing specific marketing requirements is the most consequential task in any industry, and it is even more so in the aerospace industry.

Consider that a new generation propulsion system and vehicle takes about a decade to develop and is to operate for the next two decades. Thus, the delivery vehicles concept must be based on payloads size and traffic projections of 20 to 30 years. While the possibilities and risks of objectives that must be formulated for a 30-year period seem staggering, the consequence of risk may be reduced through planning of evolutionary options. Evolutionary approaches may diminish the risk of predicting market needs, but must face the consequence of compromising the delivery cost per pound on the baseline vehicle by lower performance associated with evolution scars, complexities, and reliabilities. The benefits and limits of evolutionary concepts should be evaluated during this concept phase.

B. Payload Concepts

Because the front-end phase is so crucial to converging on a successful minimum cost project, user needs must be thoroughly researched, understood, and evaluated. There are many methods for evaluating user needs leading to solutions. Flugel's[9] conversion steps provide that understanding, and help to differentiate between user's true demands and other quality requirements. Sometimes

designer's concepts that are technically brilliant are at variance with market needs where market needs dominate. Innovations to reduce the time and cost of experiment integration, reduce the time and effort of acceptance reviews and inspections, and simplify vehicle mission planning and preparations are always invaluable marketing assets.

Experiments are selected and packaged into potential payloads by commonality of orbital altitude, inclination, insertion requirements, attitude accuracies, weight, size, shape, maximum ascent acceleration, predicted readiness and total number of missions. QFD[10] techniques may be adapted to define standard payload package sizes and characteristics. Such compilations of predicted payloads availability and their general requirements are referred to as mission models. Range of payload requirements and delivery frequencies are grouped by similarity of orbital requirements and are optimized for specific cost to form a traffic model. The traffic model establishes vehicle performances, and projects a fleet of vehicle launch rates, sizes, and quantities to accommodate payload models according to user needs, budget constraints, and operational availability.

Payloads further define mission, schedule, and launch readiness reliabilities which translate to cost to users. Reliability of the experiment delivery success is directly related to cost of insurance to the user. Slipping delivery schedule may deny the experimenter an observation opportunity which degrades the effectiveness of the experiment, and drags on the cost of personnel staffs, inventory, and storage to the user. Delaying launch countdown may degrade biological experiments and require refurbishment.

Integrating experiments into one or a family of containers, or shrouds,[11] independent of the launch vehicle site and finally stacking the containers on a ready-to-go vehicle provides a quick change-out capability to the payload. It reduces the launch vehicle integration time which decreases the operational turnaround time. It has the potential for just-in-time inventory.

C. Vehicle Concept Development

Payload package delivery requirements that drive vehicle systems requirements include payload sizes, mass, reliabilities, and orbit insertion conditions which are partially listed in figure 6 in a figure 3a matrix. By assuming a common reference, low-Earth orbit (LEO) and a standard ascent trajectory, performances of a wide variety of launch vehicle concepts delivering the total set of payload packages may be evaluated. Final mission insertion conditions from LEO may be accomplished through additional upper stages or transfer vehicles.

In this phase, launch vehicle systems parameters that must satisfy each payload package's requirements are identified, from which a wide range of vehicle concepts are developed to accommodate all firm payload packages. Vehicle concepts may be developed in three steps. Each step introduces new vehicle systems, requirements, and interactions with other systems. Each increasing step exposes more design parameters which shape the vehicle and generate more information, estimations, and interactions, which successively update and iterate parameter requirements and solutions of preceding steps. Selection criteria for baseline vehicle concepts should include performance, manufacturing and operational costs, growth characteristics, and project risks. Risk[12] is here defined as the product of probability of failure and cost for reversing that failure into a successful product.
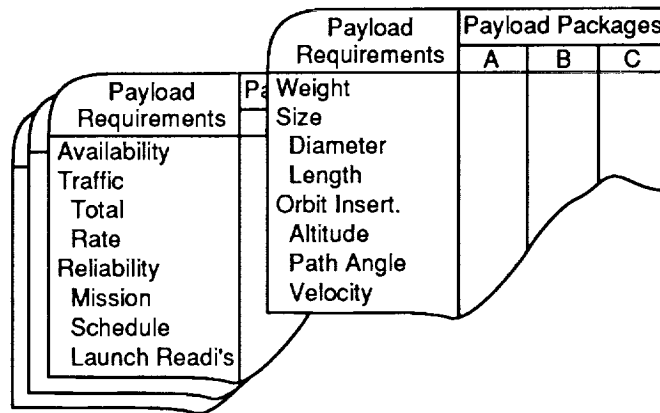
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Figure 6. Payload packages requirements.

First step combines propellant systems and staging schemes to develop first-order vehicle parameters to satisfy payload delivery energy requirements. Specifying the launch site latitude and launch azimuth, the Earth local surface velocity is established as the initial velocity of the Homman transfer orbit.[13] The final velocity is the reference LEO injection velocity. The difference of these two velocities (ΔV) specifies the propulsion energy that the vehicle must provide to the payload to achieve LEO. The vehicle model assumes a point mass and a kick-impulse method with various staging schemes, mass fractions, and propellant systems to estimate the vehicle systems' energies in terms of the required ΔV to LEO,

$$\Delta V = I_{sp1} \, g_o \, ln \, r_1 + I_{sp2} \, g_o \, ln \, r_2 + \dots .$$

Staging (subscript numerals) should split the velocity difference optimally. The specific impulse (Isp) for each stage is defined by the selected stage propellant system, and g_o is the Earth gravity constant. The propellant bulk is determined from the resulting stage mass fraction (r), which is the ratio of the propellant mass consumed by the stage and the total mass propelled by that active stage propulsion system including propellants and payload.

The propulsion system selection is the most critical driver of any vehicle concept. It drives the vehicle performance, size, reliability, and development and operational costs. There is a large choice of propulsion systems and staging options to satisfy payload delivery requirements. The vehicle may be powered by hydrocarbon, hydrogen, solid fuels, or combinations in a single stage or by more stages burning in parallel or in series. Vehicle stages may be reusable or expendable. The purpose of this step is to develop feasible concepts and options having different propulsion systems and staging schemes, and to rank their relative performance and relative development and operational costs. The rather simple analytical technique should require no extraordinary effort to explore and rank all vehicle combinations in the first step, and to carry a few of the most promising concepts to the second step.

A totally reusable, single stage to orbit and return vehicle is under study.[14] A hybrid engine accelerates the vehicle through the lower dense air and switches from air-breathing to rocket propulsion using tanked liquid oxygen at higher altitude. It assumes commercial airline operations, but it is very sensitive to vehicle weight, and is not considered a current option.

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A multistage, high-performance vehicle would consist of two propulsion systems. A high-thrust, low specific impulse (Isp) booster would expel propellant mass very rapidly and accelerate the vehicle quickly out of the Earth's gravity and atmosphere for best performance. Hydrocarbon liquid engines are especially suited for heavy lift vehicles because of very high thrust capability per engine, requiring fewer boost engines and less complexity than hydrogen engines. Production type hydrocarbon engines have achieved about 1.5 million pounds of thrust. They are expensive to develop, form coking, and require cleaning for reuse. Solid motors are cheap to develop and operate, but their reliability is less than liquids, and they are considered environmentally less desirable. Burn duration defines the solid motor diameter, which is a maximum of 150 inches and 120 seconds at current technology. Motor thrust is accommodated by the grain burn surface which determines the motor length. Current maximum thrust is 2.6 million pounds.

Hydrogen liquid engines are preferred in upper stages because their high Isp increases payload performance. The clean burn allows low maintenance for return stage reuse, but inherent system complexities have resulted in more development testing and operational checkout procedures. Current maximum thrust technology is one-third of liquid hydrocarbon engines. Ambitious programs (*Apollo*) would develop the hydrocarbon and hydrogen engines together for heavy lift vehicles, while limited budget programs might use hydrocarbon on all stages. An all-hydrogen engine vehicle is an option, if integration and operations complexities and associated reliabilities of large a cluster of engines are traded to be acceptable.

The choice of parallel versus series burn depends on available lift-off acceleration (thrust-to-weight ratio), maximum ascent acceleration allowed, propulsion reliability, and optimum performance. A two-stage, series burn would split the orbital altitude in half, and the ΔV for each stage is calculated using Homman transfers. In selecting propulsion systems, the Isp and mass fractions must be estimated to start the design process. Both are sensitive predecessor parameters and sources of iterations through all design phases. Assuming an Isp of 70 and 80 percent of the nominal performance for the first and second stages, respectively, will reduce major design iterations. Similarly, a 70-percent mass fraction should be assumed for the first and second stages to calculate propellant masses and volumes.

One concept for improving mission reliability is to ignite and monitor all liquid engines to at least 90-percent thrust before committing to launch, in which case all stages are parallel burning at lift-off. The launch vehicle would consist of a liquid engine drop-off half-stage, and a liquid engine core stage with attached payload. The staging ΔV split of this one-and-half stage to orbit is optimized for total performance from which propulsion constraints and stage propellant weights are determined. Solid motor boosters may be considered for the evolution vehicle, and its stage duration is dependent on motor technology limitations. Parallel versus series burn options trade lift-off thrust requirements with net performance. Because propulsion selection is the major design driver, vehicle concepts with several competitive propulsion schemes should be selected for the second step.

Second step assumes a vehicle stick model with lumped masses and point thrust to define a vehicle envelope ascending through space environments with standard trajectories to LEO for each selected concept. This step decomposes basic design tasks into requirements and solutions, which may be orderly developed, interacted, and tracked through systems matrices. Propellant tank diameters are restrained by logistics, payload size or first stage engine arrangements, but are otherwise optimized for tank volume and inert weight. Stage lengths are approximated from propellant volumes and diameters. Total vehicle length is estimated from stage stacking arrangements and payload sizes. Masses are lumped at stage centers of gravity, and the vehicle envelope is modeled with

cones and cylinders to estimate aerodynamic drag and center-of-pressure. The total lift-off thrust is estimated using the total vehicle weight and an assumed lift-off ratio acceleration of 1.25-g (thrust-to-weight ratio) to assure control over launch pad clearance under ground wind disturbances. The final stage thrust is limited by the payload maximum ascent acceleration requirement. If the payload is manned, then the concept may be limited to a more benign ascent acceleration.

Flight natural environments imposed on vehicle concepts through the flight trajectory include temperature, density, winds, and gravity. Wind speed, shear, frequencies, gusts, and direction vary with time and altitude and are applied for the worst month. Aerodynamics, thermal, propulsion, and vehicle control are induced environments. Aerodynamic load distributions primarily establish the center of pressure, forces, and moments, while mass distribution defines the center of mass and moment of inertia. Vehicle controls induce bending moments and shears. Moment balance (instant control) is assumed throughout the trajectory.

This step is iterated on the assumed parameters of the first step to generate more parameters and assumptions to provide a better definition of propellant systems, weights, gravity and drag losses, and stage splits and thrusts. A few of these payload and vehicle concept parameters interacting and driving options in the first and second steps are listed in figure 7 in a figure 3b format. The most conspicuous and significant single driver in each concept is the propellant system selection, which sizes major structural components and defines the overall vehicle configuration. The engine is the single most expensive element to manufacture and operate. Induced environments are directly governed by the vehicle aerodynamic envelope and mass arrangements. Since vehicle configuration details, masses, and aerodynamics characteristics are not fully developed until the end of design, all trajectory, integration, and interface analyses are in a constant state of iterations and convergence. This step concludes with selection of third step candidates through criteria formulated by concurrent engineering and using QFD techniques.
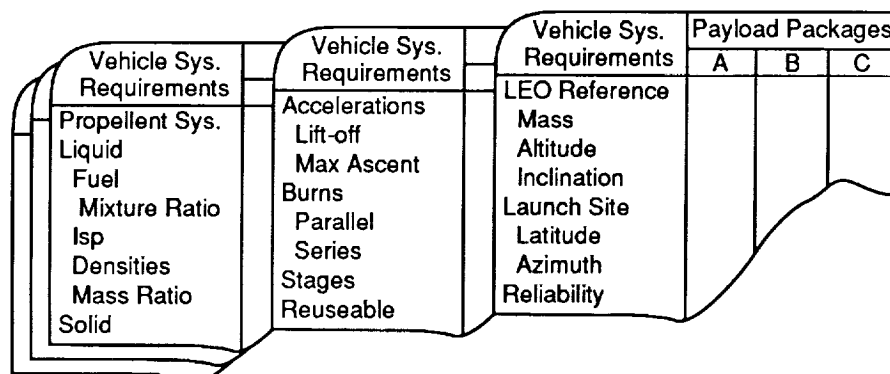
Figure 7. Vehicle-derived requirements.

Third step is a vehicle configuration development of each selected vehicle concept and all its interacting systems and elements leading to candidates for the definition phase. Propellant tanks are sized and arranged to optimize load paths. Stage configurations and weights are refined through limited structural analysis. Vehicle control laws are incorporated into standard trajectories to define loads and thrust vector rates. Engine size is estimated from numbers required to satisfy lift-off thrust, and from commonality requirements with other stages and vehicle growth. Engine-out and throttling requirements are also considered.

This step further compares and ranks concepts of each propellant system and combinations for further screening of performance, reliability, operations, and cost by concurrent engineering. Preliminary wind tunnel model results of complex aerodynamic and aeroheating concepts should be included in the final concept performance iteration. Vehicle systems should be detailed to a level appropriate for identifying operational facilities and total concept costing. Before discarding a potentially brilliant concept that did not pass all payload requirements and selection criteria, corresponding requirements should be reexamined for that flexibility that unbinds creativity.

Concept phase analysis should produce a firm set of payload and vehicle configuration requirements with a first-order scenario of the project life cycle including development, manufacture, and operations. It should contain a complete projection of all major supporting technologies, skills, facilities, flow inventories, logistics, special handling equipment, data links, operations, etc., and rough-order-magnitude (ROM) cost to develop and maintain them. Figure 8 lists typically derived vehicle systems parameters leading to element concept requirements and options to be developed in parallel with the vehicle concept and with similar TQM methods during the third concept step. There should be no surprises in going into the definition phase. A misguided propellant system and staging selection passed on to the next design phase will precipitate extensive recycling into the concept phase. A high-leverage concept phase should pursue all necessary off-line studies, and even overlap critical concepts into the definition phase as needed to understand risks and cost sensitivities. The larger and more ambitious the project, the more definition overlapping is required to rough out total mission scope, shape major vehicle systems, identify critical challenges, and establish life-cycle cost targets.
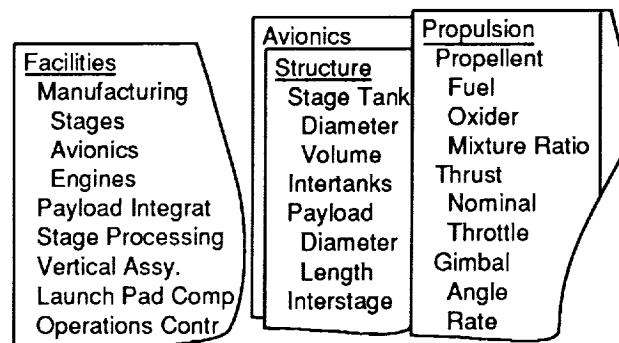
Figure 8. Vehicle systems design parameters.

V. DEFINITION PHASE

The definition phase is a detailed continuation of the concept process in identifying design parameters and requirements of the selected vehicle concept, and in developing solution options and selection criteria leading to a vehicle configuration and to systems, elements, and components preliminary designs. Results encompass a detailed definition of total vehicle systems and systems elements including flight hardware, support equipment, software, personnel, etc., and the complete operational use definition, configuration description, preliminary design, and systems operational plans. Requirements identified in this phase are documented as specifications on vehicle configuration, systems, elements, and interfaces to be verified by vehicle design analysis and preliminary

tests. A ROM cost of elements' total life cycle are also required. Concurrent engineering teams develop selection criteria and select and verify solutions. Teams include flight, propulsion, structures, avionics and facilities systems, and should have representation from weights, reliability, manufacturing, verification, operations, safety, and costing disciplines.

A. Configuration Development and Options

Because the quality leverage in this phase is less than the concept phase, inappropriate requirements and unsatisfactory solutions that must be reworked become increasingly more costly. Consequently, an orderly and visible approach to this phase is to established a select set of design parameters into a vehicle systems matrix, and expanding it with all interacting systems parameters, including operations parameter. Tasks identify requirements which generate solution options.

Generating solutions to satisfy requirements is a critical step in this phase in that the best option generated may not be the most suitable. A recourse is to generate as many solutions as possible which are limited only by the experience, knowledge, and competence of the designer, the information and maturity of depending technologies, and the level of analyses necessary to validate concepts.

Figure 9 is a partial matrix (fig. 3c format) of significant vehicle parameters interacting with vehicle systems and elements required to define a vehicle configuration and facilities. It is a cut at identifying task and design parameter interfaces with vehicle systems across the rows. Each matrix slot lists all major interrelated tasks. Decomposed design parameters along columns are not necessarily ordered according to an efficient flow of their interactions. Steward's technique is most appropriate for reordering column tasks separately and off-line for optimum flow of design information and iterations. Note that common parameters to all systems and elements are reliability, weight, and costs, which may be suggested to establish a staff for providing a running tally and control of each. Narratives relative to requirements and option development in this phase are quantified through detailed math models and standard engineering design practices.

Companion matrices should also be developed for evolution concepts. If different sized payloads are assumed to be delivered to a reference orbit through an evolutionary launch vehicle buildup, the baseline vehicle must consider unit delivery cost and performance compromised by the evolution scars with the cost of stretching baseline manufacturing facilities and tooling, engine clusters, and operational limits to define the evolved payload capability and delivery cost. These types of considerations should be reflected throughout this phase in defining the basic vehicle. Systems requirements should not be so restrictive as to stifle innovation and option developments.

A critical user requirement identified in figure 9 is reliability: reliability that the payload can be committed to a specific launch date; reliability that lift-off will occur within a specified time tolerance; reliability of flight success. The date-related reliability may be satisfied by the flight hardware flow, fleet size, turnaround time, and facilities to accommodate them. A catastrophic launch pad failure would devastate that requirement, and a contingency plan is necessary to restore the project. Flight reliability is achieved through operations rules, fail-safe designs, redundancies, countdown checks, and liquid engines startup to 90-percent minimum thrust before lift-off release. The all-liquid engines startup capability of parallel burn concepts should provide greater ascent reliability.

Vehicle Parameters	Vehicle Systems				
	Flight	Propulsion	Structures	Avionics	Facilities
Reliability	Mission Window	Start Thrust	Stress Stability	Phase db	Turnaround Readiness
Cost	Budget & Estimate	Budget & Estimate	Budget & Estimate	Budget & Estimate	Budget & Estimate
Velocities: - Orbital - Launch	Energy to Orbit, (Delta Vel.)	Specific impulse	Mass Ratio Tank Volume	GN & C	Assembly Launch Command
Staging	Optimum delta V	Propellent systems	Tank Vol's. Interstage	Cut-off Separation Start-Up	Assembly Stacking
Weights	Distribution Loads Staging	Propellents Engines Residuals	Tanks/Inter Interfaces Mounts	Computers TVC Data Sys.	Handling and launch Equipment
Thrust	Accelerations - Lift-Off - Max Flight	Engines - Sizes - Numbers	Load Paths Thrust Stru.	Engines - Control - Monitor	Launch Release Flame Bucket
Diameter	Aero. Drag C.P. Stability.	Engine arrange'nt	Vehicle length	TVC Stab. Slosh Freq.	Transport limits
Propellent Pressures	Residuals	NPSP Heat Exch'r	End-Closure weights	Monitor & control	Launch Start pressure
Mixture Ratio	Delta Vel.	Isp	Tank Sizes	M.R. Control	Storage, Fill
Tank Arrange	C.P. & C.G. stability	Fuel and lox NPSP	Shell crit. load paths	Slosh freq. TVC	Fill, Geyser, Vent

Figure 9. Vehicle parameters and interacting systems matrix.

Unscheduled launch holds are usually caused by failure of the propellant tanking system, count-down checkout anomalies, and inappropriate weather conditions. The best solution to launch-hold reliability is through robust design. From the vehicle side, any design improvement in flight reliability is an improvement on launch-hold reliability. Pareto's principle is an efficient approach to look for significant improvements. Lift-off with a redundant engine down or computer module out may improve hold reliability, but a no engine or computer out would better serve flight reliability from more fateful consequences.

Realistic reliability values may be specified at the systems level through the understanding of potential solutions and consequences of schedules, holds, and flight reliabilities on the mission systems. As systems reliabilities are translated to subsystems, elements, and components levels, reliability values increase inversely.

Expendable vehicle concepts and a large fleet size requirement sometimes suggest designing beyond craft production to profit from commercial quantity production technologies for improving

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quality while reducing cost. Emphases on thermal and stress fatigue life, fracture mechanics design, bearing endurance, aging, and inspections are significantly relaxed on expendable vehicles. Development of recovery and refurbishment techniques and their facilities and operations are averted.

Man-rated requirement on a basically unmanned launch vehicle shifts rescue requirements to the occasionally manned payload as in earlier programs. Man-rating requirements imposed on vehicle systems are no more stringent than the high reliability infringed on elements and components of large, costly unmanned launch vehicles and payloads. Since most launch-holds and vehicle failures are caused by liquid engine component malfunctions, engine simplicity and robustness are the premier challenges. Vehicle reliability may be further increased by reducing the total number of engines required, which reduces the complexity of integrating multiple engines and the inherent complexity of each additional engine in itself. While the vehicle lift-off thrust requirement is derived from the lift-off acceleration requirement, engine types, sizes and numbers required are derived from optimizing the split stage performances to the reference orbit.

Vehicle performance was earlier noted to be dominated by flight system environments and the propulsion system, all of which interface with structural and avionics systems. The sizing, arrangement, and integration of these systems are further influenced by interfaces with systems elements, operations, and handling. Flight hardware performance and reliability requirements do not necessarily reign over ground equipment requirements, and must be traded with launch preparations, check-out equipment, and launch-time reliability requirements.

In developing the vehicle configuration, tank diameters must not exceed transportation limits. Making the diameter as large as is practical provides the potential for increasing the tank volume for evolution vehicles by stretching only the tooling length with minimum manufacturing and operational cost. It should ultimately be compatible with the payload package, logistics, handling operations, and optimum volume-to-weight ratio.

As the propellant tank diameter increases, the slosh mass increases, and the frequency may approach and conflict with the vehicle control frequency. Slosh baffles may be used to damp the slosh frequency. Slosh transient effects on attitude control rates become more pronounced as the vehicle mass decreases near cutoff. Another slosh interface is the propellant pressurant. As the slosh mass increases due to larger diameter, the slosh wave surface increases which increases the rate of condensing gas, and requires an increase in pressurant gas generation. Slosh above the vehicle center of mass tends to destablize the vehicle, while slosh mass below the vehicle center of mass damps out for a more stable arrangement. Fuel and oxidized tank arrangements are resolved through the propulsion and structures systems integration analysis, from which slosh frequency margin requirements are determined.

Increasing the tank diameter decreases the vehicle length which reduces the couple arm between the aerodynamic center-of-pressure and the center-of-mass and makes the vehicle more stable. However, the moment arm from center-of-mass to engine hinge is also shortened requiring larger gimbal angle. An early engine-out condition may also require larger gimbal angle.

Tank volume requirements are based on propellant volume consumption to orbit plus pressurant gas volume required to sustain engine pump net positive suction pressure (NPSP) from engine startup to cutoff. Additional propellant volume is required for the propellant consumed from engine

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startup to launch release, and for minimum cutoff residuals required to prevent pump cavitation. Fuel residual bias is calculated to insure that fuel does not deplete at engine cutoff before the oxidizer to prevent possible engine destruction.

Though earlier liquid oxygen (lox) tanks have been arranged forward as well as aft of fuel tanks, there are preferences. Lox content being heavier than the fuel, mounting it closest to the liquid engine thrust structure reduces the compression load path for a lighter overall shell structure. From a filling operations consideration, a shorter lox line to the engine reduces the bubbling geyser effect which may be a very significant operations factor. Having the fuel tank forward improves the fuel pump NPSP. If solid rocket boosters are a serious consideration for the evolutionary launch vehicle, the lox tank forward may be a better overall arrangement. Solid motor thrust is reacted on the forward end of the booster, and because of the booster length accommodation above the launch platform, the shortest load path from the rocket is to the intertank aft of the heavy lox tank. These options are traded with payload cost per pound to finalize tank arrangement requirements for the basic vehicle configuration and its evolution.

Tank end-closures are usually elliptically shaped, but may not be the best configuration for performance and cost. The lox and fuel tank forward domes are designed primarily for internal pressure. Cassinian domes may provide as much volume as an ellipse in a shorter length and with less discontinuity at the edges for a total vehicle net weight saving. The shape is limited by the ratio of the two meridional curvatures leading to shell buckling. Both forward end-closures may be manufactured from a common tool, and both may be applicable to the evolution vehicle version. Aft end-closures are designed for pressure caused by the pressurant, propellant static head, and rebound inertia load caused by engine shutdown during on-pad abort. The lox aft end closure experiences the greater pressure, and may be even greater for the evolution vehicle. Before concluding to use the same tooling as forward domes, a configuration should be explored that optimizes the performance of the combined aft dome shape in tension with the tank and intertank-interstage barrel lengths in compression. The main objective is to obtain the maximum mass fraction at minimum cost. Manufacturing cost of expendable tanks recur with every mission.

Tank pressure requirement is another multi-interface trade. There is the engine energy trade between pump energy reduction to increase NPSP by increasing pressurant pressure, and the heat exchanger energy increase required to increase pressurant flow rate and pressure. Increasing the tank pressure may reduce the barrel compression load but increases end-closure membrane loads. Increasing the pressure increases the residual weight at engine cut-off which is a one-to-one payload penalty on last stage to orbit.

Engine arrangement and thrust structure must be accommodated within the stage diameter. Thrust structure must accommodate sustainer (and possible drop-off) engine clusters. Clearance must be provided for feed lines, plume impingement, engine gimbal, and thrust vector control (TVC) system. The vehicle propulsion system interface with ground operations and reliabilities must be liberally estimated. These interfaces include fill and drain, pre-start tank pressurant, purge, vent facility, and launch platform. Cryogenic tank insulations depend on loading and standby time requirements, as well as on aeroheating conditions. Lox feed line is insulated to control geyser effects.

At some point in the vehicle systems matrix process, a sufficient number of interfacing element parameters have been identified to initiate new matrices of element parameters interacting with element components in order to define vehicle elements and components. Elements are decomposed

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into design parameter and component tasks and processed as were the vehicle systems matrices, and as required to integrate into a launch vehicle configuration definition. Long lead-time vehicle elements and components are identified and cautiously defined to minimize integration problems which sometimes compromise performance and reliability or may require high-tech innovations and modifications to comply with mission requirements.

In defining the engine element of the propulsion system, cost and reliability are the new focus over performance, though high specific impulse and thrust-to-weight ratio are among primary criteria for reusable engines. Expendable engines trade large design margins to provide high reliability and low manufacturing costs. Reusable engines require moderate margins, and high manufacturing costs are traded with low operating costs and high durability. Element decomposition and component options and definition are systems specific.

Avionics systems elements consist of electronic devices, instruments, and software that sense, affect guidance, navigation, control, communication, and monitoring. Monitoring parameters include engine startup, shutdown, thrust level, thrust vector control, propellant and pressurant management, and thrust valve controls. Health monitoring checks temperatures, pressures, accelerations, and electrical services. Element solution options are based on increasing performance, reliability, and reducing labor and operational costs. Standard interfaces, hardware, and software reduce operations costs.

Structural element requirements are generic and are dominated by high strength-to-weight ratio, high stiffness-to-weight ratio, dimensional stability, and by materials compatibility with interfacing environments and fabrication options.

Facilities and equipment element options development are vehicle system specific, and address fleet size, payload traffic, production rate, and storage costs. Vehicle design interactions with facilities include special handling equipment, hazardous material treatment, seal and connection leakage prevention and testing, robustness, and automation.

TQM techniques are applied to each of these elements and their interfaces through this definition phase process, which includes parameter decomposition, requirements identification, solution options, trades, selection criteria, definition, and preliminary designs.

B. Trades and Technologies

From user requirements to preliminary design, the systems analysis process was seen to consist of decomposing systems design parameters and tasks to the lowest practical level, and then developing requirements and optional solutions to satisfy them. As tier levels of parameters increase, the list of requirements increases, and design options to satisfy each increase even more. Furthermore, development of design options and selection of the best interacting option become more difficult with increasing tier levels. The method for enhancing and selecting solution options to best satisfy requirements is through trades, concurrent engineering, and technology.

Just as critical a task as developing design options is the evaluation and selection of the best option. The expected performance of a bad choice is seldom regained through clever detail design. Gut feeling decisions are more likely to produce wrong selections, and teams are more likely to select and enhance the best option. A selection method is to allow concurrent engineering working

teams to develop selection criteria and apply them through a proven decision-making technique. Selection criteria most essential to decision making are related to resources and performances, such as funds, time, manpower, skills, product weight, reliability, safety, vulnerability, repeatability, manufacturing reproducibility, test cost, operations, risks, etc.

There are many option selection techniques, and one suggested by Pugh[15] compares one option against another and enhances it in the process. The technique uses a matrix of criteria versus options for complete visibility. It uses one option as a datum to compare all other options with a "plus" or "minus" compliance with selection criteria. All evaluated concepts are then reviewed for possibly modifying them to pass the criteria. Weak options are eliminated until one strong concept persists. Another more detailed selection technique may be adapted from Akao's quality function deployment method.[10]

Implicit in each option is a dominant technology which may be classified as a low or high existing technology, a new technology to be developed, or an existing technology to be adapted in a new way. The brilliance of an option is the selection and adaptation of technology, but also is its risk of performance and cost. Even so, in developing options, a designer must sense the level of technology a project can afford. He recognizes the performance benefits in applying low-technology to booster hardware and high-tech in stages to orbit. He perceives that a project could weaken if burdened with more than one major new technology. He particularly realizes that existing, low-tech options are low performance risks. Then what level of technology is an unacceptable risk, and why should any new challenge with risks even be proposed or selected?

A common motivation for using the highest technology possible is competition. The automotive, electronic, and particularly defense industries are engaged in providing highest and latest technologies for survival in global competition. However, NASA's large vehicles and space structures have no immediate competition, nor does NASA pretend to promote technology challenges in them for the sake of commercial spinoffs. Then the most obvious reason for launch vehicle industries to engage in new online technology is to be more productive; more productive in design, manufacturing, verification, and operations.

One criterion for reducing the timeliness and cost risk in selecting options with advanced technology may be that the proposed technology application must be verified in principle by the end of the preliminary design. Projects with relatively short life-cycles would discourage any basic research of new technologies, but would embrace adaptation of existing technologies that would improve performance and combine low-cost manufacturing with high-quality product. It should be incumbent upon designers to develop options with and without adapted technologies in search of more productive products, though recognizing that evaluation and selection may be beyond their individual capabilities, as noted in the following example.

Filament-wound composite shells may be a commercially established technology, but its adaptation to an intertank shell must be uniquely developed for structural properties scaling, dimensional stability, and compatibility with cryogenic tank connections. Detection and maintenance of handling damage and delamination, etc., must be understood. A structures-materials concurrent engineering team would investigate availability or expandability of winding and curing facilities and related experience base. In recognizing risk as the product of failure probability and cost of consequence, the team would evaluate total cost of the adapted technology shell, including risk of failures and modifications in the development process; manufacturing, bottlenecks, spares, inspection, and

rejection rate over the total project life; stretched schedules; and improved payload performance. The net cost of risk and improvements of the adapted technology option would be compared with conventional, low risk, metallic intertank shells.

This example illustrates many features of the definition phase. A designer can develop an adapted technology option alone, but cannot evaluate it alone. The concurrent engineering team should consist of the necessary skills and experiences to investigate, analyze, and work it through reviews, task assignments, and exchanges. Schedules, net cost, performance, and operation gains are among dominant selection criteria. Just as important and obvious is that the proposed option and risk evaluation processes discussed are identical to product improvement processes conducted during operational phases. So why not incorporate the improvement process during the definition phase for a high-quality leverage savings, even though it may extend the phase time? One TQM maxim is *do it right the first time.*

Advanced computers, as applied in drawing rooms and shops, are a common type of adapted high-technology invisible to launch vehicle products, but having ever expanding and improving potentials of being more productive to a project. Current applications are in aiding design tools, electronic data exchange, dynamics analysis and simulations, detailed working mockups, controlling machine tools, increasing productivity and quality of manufacturing processes, and measuring and controlling quality instruments. More can be done to facilitate verification testing, to hasten data recording preparations and interpretations, and to provide comprehensive response graphics. There are even more computer-technology adaptation opportunities in ground operations to automate and reduce human errors, to monitor, and to expedite flight preparations. Electronic architectural walk-through technology may be adapted to assess maintenance access and workstation design layouts.

Technology risks are sometimes unexpected in excessively scaling existing or similarly processed products. Stiffness and strength properties of filament-wound case samples were noted to decrease with increasing model sizes[16] because of compaction limitations and because of extended epoxy pot-life required by longer winding time. The H-1 hydrocarbon engine combustion stability phenomenon was not well known when it was scaled over six times on the F-1 engine which resulted in a very costly engineering bottleneck. Solid motor propellant mechanics is not adequately characterized to predict its storage and combustion integrity. New design concepts, grain formulations, and processes should be cautiously modified from the currently experienced base.

Since new and advanced technology risks may no longer be affordable within specific launch vehicle projects, many technology improvements are being funded under off-line programs, such as the Civil Space Technology Initiative (CSTI). This program may be a trend for mobilizing and focusing all aerospace technology developments. CSTI[17] includes development and demonstration in advanced design and analysis tools, materials, processes, and highly reliable liquid engine components and controls.

C. Design Margins and Reliability

Though design margins and reliability are generally perceived as two distinctly different concepts, margins are applied to coarse predictions of functions defined in conceptual and definition phases, and eventually converge to the guaranteed reliabilities in the design phase. Perhaps, the connection of margins and reliabilities roles may be better understood through the visualization of the reliability concept (fig. 10).
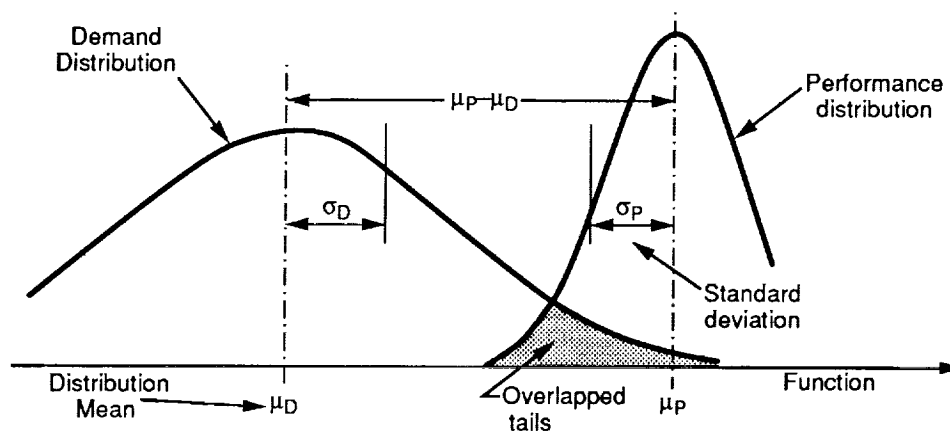
Figure 10. Reliability concept of demand and performance distributions.

Each system, element, and component is designed to "perform" a minimum specified function to satisfy a maximum derived "demand" (or requirement). Minimum and maximum stated values suggest a statistical distribution about their expected means. Figure 10 pictures the probability density distribution of the "demanded" function and the probability density distribution of the hardware "performance" (capability) to satisfy that demand. Their overlapping tails suggest that a weak performance will encounter an excessive demand to cause a functional failure. This tail overlap is governed by the difference of the two distribution means (μ_P–μ_D) which, divided by their combined standard deviations, may be related to a reliability[18] value. The greater the reliability specified, the greater is the mean difference required for the same standard deviations. Applying a preliminary margin "m" to the demand increases the means difference [μ_P–$(1+m)\mu_D$] and the reliability.

In stepping through the conceptual and definition phases, it was clear that as vehicle systems and elements were progressively decomposed, more requirements and performances were generated and estimated, which iterated and increased earlier estimated demands and performances. Each decomposition and iteration cycle introduced more estimations, interactions, details, and information which increased demands. Generally, demand continues to change beyond the final design phase, but it is not practical to continuously change performance designs with every demand change. To avoid frequent performance revisions resulting from iteration demand increases, and to better converge on the specified reliability, each critical demand is initially increased (based on experience) to separate the demand distribution mean from the performance mean with a comfortable sacrificial margin.

Assigning initial sacrificial margins to demands and defining functional performances to satisfy them, critical margins will: (1) be incrementally consumed with each iteration that increases demand without having to change performance of design, (2) not disturb other interacting hardware performances with each iteration, and (3) have a better prospect of converging to specified performance reliability at hardware verification. When the reliability is not verified at this lowest quality leverage, trimming of demand requirements is often futile. The most common practice has been to increase the hardware performance through higher technology and very costly bottleneck development.

Vehicle systems' weights increase through all phases resulting from iterations with wind tunnel aerodynamics performance updates, detailed trajectory and control revisions, adjusted propellant requirements, new residuals requirements, structural loads cycles, services and separation

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devices, etc. If at least a 30-percent margin was not applied to weight estimates of complex vehicle systems at the conceptual phase, and 15 percent after preliminary design, the selected engine thrust level requirement could be seriously underestimated at some point in the design phase. The vehicle would then have to be redesigned with an additional engine, or the engine performance would have to increase though higher technology and reduced life.

There are many other function demands that require margin imposition during the conceptual and definition phases. Cost grows with each arising demand in performance, its manufacture and operation. A cost uncertainty margin of 30 percent at conceptual phase is not excessive. Payload density is rather low which may cause size to be more critical than the specified weight. Payload operational center-of-mass demands should have the widest latitude practical to avoid excessive payload planning and preparations, and to avoid underestimating vehicle control performance. Engine performance should incorporate margins to specific impulse, thrust, pressurant heat exchangers, critical speeds, bearing loads, high temperature materials properties, etc. Structural loads start with a 200-percent margin on the dynamics load component which is chipped away to less than 15 percent at the end of preliminary design of stubby vehicles. Inertial margin estimates should reflect weight margins.

Design margins and reliabilities should be imposed on all other function demands, such as propulsion performance, controls, avionics, structures, heat transfer, aerodynamics, aeroheating, materials, processes, facilities, logistics, and operations. Most often underestimated margins are on facilities and operations demands and costs. Another type design margin championed by robust methods is designing to low technology materials, processes, and manufacturing so as to leave improvement margins at low cost.

D. Preliminary Design Definition

The definition phase expanded the selected vehicle configuration to launch vehicle systems, systems elements, and element components definitions. Selecting the most suitable definitions through these hierarchic levels from a variety of architectures is a highly creative and skilled activity. The more completely developed are the solution definitions in this phase, the less design effort is impending in the next lower quality leverage phase, resulting in a briefer effort and less costly total systems design and final product.

Central to the definition phase is the optimum selection of hydrogen versus hydrocarbon propellant systems from operations and cost awareness. The high energy of the hydrogen system makes it less sensitive to weight which may be applied to increase robustness, but its inherent limited engine thrust level requires more boost engines which increases the propulsion complexity and integration while reducing reliability. Payload performance is traded with reliabilities to launch-on-time and mission success, and with recurring costs of manufacturing and integration. Operational costs must compare transportation, processing, checkout, health monitoring, skills, and personnel levels. If one scheme is technically and economically superior, but constrained by high level requirement, the requirement must be challenged and resolved. Every vehicle system and element is so dominated by the propellant system selection that backtracking from beyond this quality leverage point would constitute a major design change and design cost overrun.

Coming out of the definition phase should be complete sets of preliminary design definitions of launch vehicle configuration, systems and interfaces, elements of each vehicle system and element interfaces, and payload and stage attachments and separation schemes. Definition sets should include centrally stored electronic layout drawings and specifications, estimated positive margins on reliabilities, weights, costs, systems preliminary test data, natural and calculated induced environments, systems trades and rationale developed to justify them, and systems and elements electronic mockups.

Element preliminary design definitions should include: major components layouts; technology challenges and estimated risks; technology level of material selections, availability, process, application sensitivities, and alternatives; preliminary test data on rare phenomena; interface environments; and inspection and maintenance accesses. Element preliminary design definitions should also include: critical trades analyses, assumptions and conclusions of all discipline analyses, software tools used and estimates of uncertainties, and response verification plans. Referenced standards documents and handbooks should be uniquely tailored.

Partial prototypes of complex shapes, new processes, and innovative techniques should be verified during this phase to provide the designer an understanding of their performance and limits. Component behavior too difficult to model should also be supported through bench tests or brief prototypes. Long lead-time elements and components that were prematurely defined should be identified and assessed for risk and contingencies.

Preliminary design of the vehicle configuration and elements represents an optimization of components and select design parameters with supporting narratives on environments, interfaces, reliabilities, support, skills, logistics, operations, and costs.

VI. DESIGN PHASE

Design phase is the final systems phase and perhaps the most consequential because its detailed design must fit and function as an integrated whole. It is also in the lowest design quality leverage. This phase must proceed with detailed bottoms-up costing adjustments. The systems analysis must penetrate all final component designs for compliance with all tiers of specifications and requirements, and to amend emanating deficiencies through all relevant upstream design phases. It must assess and assure that all integration conflicts and issues are identified and resolved through all levels of components and systems. It must further analyze and modify detailed component designs and their integrations for (1) high quality performance, (2) manufacture, (3) verification, and (4) operations at lowest cost.

A brilliant concept can degenerate through poor design and still comply with specifications. But quality analysis goes beyond specifications. Quality requires performance to be robust and least sensitive to environmental fluctuations. It requires designs to facilitate manufacture so as to reduce rejects and cost. It requires design to be simple to verify so as to avoid acceptance of defective products. Quality operations are mostly designed into the product. Quality design analysis looks to these four steps downstream in the hardware process and initiates the highest quality leverage of detailed hardware design. Quality design analysis is the focus of this systems design phase.

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A. Quality Performance

Reliability and costs were noted to be common control parameters in a total systems design. Weight was another common parameter peculiar only to flight articles which translates into cost of payload delivery. The goal of quality performance of functional products is to improve on these parameters while achieving ideal response under all intended operating conditions. If the ideal performance is specified, Phadke's robust design method may be one technique for realizing that goal.

Quality characteristic is the difference between the output and targeted performance values, and may be classified by its response to improve targeted performances. A quality characteristic of smaller-is-better would have a performance target of zero. Joint leakages are a common source of quality loss in launch preparations and delays. Response time, structural weight, material flaws, and corrosion are other examples. Larger-is-better would have a target approaching infinity were it not inherently limited or restrained by other interacting characteristics. Material strength and specific impulse are larger-is-better examples with limited targets. Normal-is-better may be characterized by a fixed target for static problems and an output-proportional-to-input moving target for dynamics problems. Conditioned power source, sensors, and servomotors are common examples where the standard deviation is minimized first and the mean is then adjusted to the target value.

An orderly approach to quality performance analysis would review all product functional responses, and would identify quality characteristics, deficiencies, and sources of variations. Criteria for selecting candidates for quality performance analysis are the consequence of performance variation. Consequence may be judged by cost of functional degradation, operational delays, and effects on performance of other interacting systems. Consequence may be derived from fault tree analysis, informal failure mode and effect analysis (FMEA), or modified risk analysis. Priority on analysis is based on risk and Pareto's principle.[19]

A functional product may be analyzed for quality performance through Phadke's robust design methodology which draws extensively from statistical techniques. The ideal performance of the selected functional product is defined by a theoretical model which relates the functional response with associated design parameters. A quadratic function is used to express its quality characteristics, and influencing parameters are identified. Three of the most common types of design parameters that influence quality characteristics are signal, noise, and control. Signal parameter levels are set by the user to produce the desired functional response, such as speed, thrust, and frequency. Noise parameters are difficult or expensive to control. They deviate from target values through unit-to-unit variation resulting from manufacturing processes and through deterioration from aging and wear. Control parameters are specified by the designer to minimize noise parameters which may or may not change the cost of the product. Tolerance factors are control parameters that affect costs.

The intent of robust design is to improve quality through parameter design without increasing cost. Parameter design employs orthogonal array techniques to reduce the number of parametric variations and combinations required to determine the most significant signal-to-noise ratio effects, leading to optimum control parameter level adjustment. After parameter design analysis is completed, tolerance design may be necessary to bring the performance to target. Tolerance design trades off quality loss due to variations in performance with cost increase to tighten manufacturing tolerance and to use higher grade materials and components. Parameters that have no effect on signal-to-noise ratio are adjusted to cost, reliability, operations, or other quality considerations.

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Robust design analysis strives to make product performance insensitive to external, unit-to-unit, and deterioration noise parameters. It aims for the widest operating environment, low grade components and materials, and wider manufacturing tolerances and variations for least cost product and operation. Developing total quality into detailed design may be better assured through design accommodation of downstream customer expectations in manufacturing, verification, and operations.

B. Manufacturing

The role of systems design analysis in this manufacturing step is to integrate performance parameter combinations and levels resolved in the quality performance step with manufacturing demands to increase yield and reduce costs which include reduction in unit-to-unit parameter variations, quality control system, and rejection rates of defective parts. If product design parameters are too complex, the product will be difficult to reproduce. If it is hard to assemble, then it will incur assembly errors. Manufacturing customer expectations must be considered in the detailed design in which the customers are processors, machinists, welders, assemblers, handlers, etc.

With innovation, Akao's[10] QFD method may be combined with robust performance demands for adaptation to a large class of designs for quality manufacturing. The QFD method is a team effort converting levels of manufacturing demanded qualities into design conditions through a set of matrices. As in most thought-generating problems, results are a reflection of the relevance and experience of the team. Level of details must be prioritized and limited to major demands.

The method decomposes a product to its parts level and generates manufacturing quality demands that satisfy quality performance design parameters developed in the quality performance step. The "what" required by performance demand is related to the "how" it is to be manufactured in matrix form. Quality "what" demands are correlated with strongest quality "how" characteristics. "How much" precision is required of the "how" demand to satisfy the "what" demand is added to the matrix. Quality characteristics are configurations, dimensions, process durability, etc. Processes or technologies that achieve manufacturing quality demands are researched, and candidates are selected for least cost and for meeting or maximizing required precisions. Selections are compared with facility conditions and capabilities. Inspection standards are established, and factors that affect control points in manufacturing are identified. The assembly process is developed next, and control points for assembly are established similarly to the parts process. Resulting quality characteristic precisions achievable through selected manufacturing techniques are expressed in engineering language and converted into design plans and specifications. Caution must be exercised throughout the quality analysis to avoid bottlenecks that limit quality and yield, and that increase cost. Engineering bottlenecks arise when quality targets are set at higher levels than previously experienced and levels are difficult to achieve.

Manufacturing cost reductions may be generally realized through efficient use of materials, new processes, flexible production techniques, robots, and others. Trading a little performance for more common and reliable production materials may reduce the material as well as machining, welding, or casting costs. Welds that cannot be inspected must be relocated or eliminated. Reducing the number of unique parts reduces cost of assembly, logistics, and learning. Using wider margins assures manufacturing quality, and may even achieve process control with minimum inspection.

Investment castings have been shown to reduce cost of welds and machining.[20] Bolted construction of nonweight-critical components may be used to reduce up to half the cost of weld

requirements. Compare a typical joint weld sequence with bolted flanges. A weld material property sample must be fabricated and tested. Mating surfaces of a butt-weld joint must be machined and must have a machined backup tool. The joint must be fitted, welded, and penetrate inspected. A flanged joint requires the following: rough machine two flanges, face flanges and cut grooves, drill clearance holes on one flange and drill and tap on the other, install seal and bolts, and torque. Pugh discusses many design techniques which provide insights to designing for low-cost products.

C. Verification

This design verification step is committed to assuring that all product design details and specifications comply with all product requirements developed through systems design analysis phases. The most common verification methods are analysis and test. Systems design objectives that must be verified and controlled are performance, reliability, and cost.

The first order of verification is a thorough and refined analyses of a design's final iteration and updated definition of subsystems down to components level as necessary to confirm targeted performance. This verification analysis is a continuance of design analysis with focus on final configuration, induced environments, interfaces, and refined models. Analysis methodologies encompass statistical and probabilistic techniques, and such computational tools as finite element (FEM), boundary element (BEM), and computational fluid dynamics (CFD). Critical assumptions are modified by timely off-line technology experiments, analytical simulations, and detailed design characteristics and data derived from matured interacting elements and components.

Launch vehicle subsystem and interface performances to be verified include propulsion, structures, mechanical, electrical, thermal, avionics, and facilities. Associated analytical disciplines include propulsion, trajectory and payload performance, mass distribution, dynamics, loads, structures, materials and processing, controls, electrical power, software, communication, tracking, instrumentation, and operations.

Quality performance and manufacturing characteristics developed in prior steps must also be verified to assure that their quality was not mutated by updates. Quality verification further implies that basic functional responses will meet or exceed specified quality performances for specified durations with specified reliabilities. Products whose characteristic qualities cannot be reliably sustained over the specified period may be identified by their application in new technology, materials, or mechanisms.

Quality assurance methods are still evolving. Their criteria should consider whether the fading quality of a product will continue to function, will affect another product function, or will not interfere with component functions as a whole. Reliability of the parts assures reliability of the assembly. A fault tree analysis may be used to connect the top fault event to the basic cause in an assembly. A technique for determining failure criticality is the failure mode and effects analysis supported by reliability experience.

Cost is verified for compliance with budget levels, and for balance with product quality. Cost balance is built into the design phase to orderly reduce cost while maintaining quality through Akao's QFD method. The process consists briefly of: reviewing demanded quality and its value to

the user, determining cost to develop and produce demanded quality, translating demanded quality to function and determining function cost, determining mechanism and parts cost, estimating engineering bottleneck candidate costs, and adjusting design and cost accordingly.

A design analyst's greatest fear is not so much marginal results of phenomena evaluated but a critical behavior he failed to uncover before committing the design to operations. Incomplete design analysis and sneak phenomenon are what most premature test failures are about. But there are other compelling reasons for identifying and designing tests in this phase. Tests are required to verify performances and margins, to establish operational characteristics and sensitivities, to determine primary failure mode and failure characteristics, to determine design deficiencies, to develop inspection and maintenance procedures, and to fine tune analytical model. Failure tree analysis, failure mode and effect analysis, critical item list (CIL), and Pareto's principle are techniques used to identify and select test items.

Test facilities, hardware, procedures, evaluations, and skills are expensive. Tests may be performed on prototype, protoflight, and subscale models. Tests may be limited to component levels, or all-up operations including flight. Tests may be performed to failure or to no-fail. A no-fail test provides limited experience on the article's safety, regardless of its subsequent successful operations. Reliability test criteria are generally difficult to verify directly. Sometimes safety index may be converted to test load factor, and operating load level may be traded with duration or with number of tests, etc. An abbreviated risk assessment to compare probability and cost of failure with cost of testing should be considered in critical test selection, level, and scope.

On the other hand, components and partial test articles, whose boundaries and operating conditions are difficult to simulate in an intermediate test, may also be difficult to interpret and verify their performances. Then the merits and cost of other than all-up testing must be evaluated. An option for assuring performances of critical articles that cannot be test verified before all-up testing is to increase the operating performance margin in this design phase to allow for all-up test uncertainties.

D. Operations

Low cost, reliable operational characteristics must be intentionally initiated into the total payload delivery systems at the earliest concept phase and step, and explicitly incorporated and iterated throughout the systems process. They cannot be significantly modified beyond development phase. The task of quality operations analysis through QFD is to assess how and how well these goals have been met, and to recognize payload, vehicle, and facilities customers' expectations.

The space industry's long-term payload processing goals[21] are similar to commercial airline operation standards where possible with respect to time, manpower, facilities, documentation, and conflict resolutions. Payloads should be integrated into standardized containers separate from the vehicle to facilitate processing and rapid switching. Standard interfaces and wide center-of-gravity margins should be provided payload containers for a more versatile packaging process, and to increase reliability to meet launch date. Increasing automation in payload ground handling and checkout should reduce human error and increase delivery reliability. Standard workstations should have data access to weather, ground processing status, operations, equipment, and vehicle health to support launch determinations.

Multipurpose expandable facilities[22] must accommodate a wide range of future vehicles with better utilization of less manpower and with shorter schedules. Launch pads must have hold-down engine-shutdown capability, be flexible and in sufficient numbers to serve different size vehicles, and assure schedules and damage recovery. Preparation time should be reduced through more use of automation and electronics to improve or eliminate checkout, and apply multiple testing and continuous health monitoring. Vehicles should be design for off-line integration and processing to reduce turnaround time.

Vehicles should be designed for reliable low-cost operations, and should incorporate and share the same payload and facilities interfacing features. The vehicle should be designed robustly to increase reliability, operability, and affordability.[23] It should simplify off-line preparations or eliminate time consuming critical path tasks, leak check, and verification. It should use computerized information and communication systems, and develop an avionics enhancement system to integrate health monitoring, fault identity and isolation, adaptive guidance, flexible mission planning and all weather flying, and multipath redundancy. Design should provide large margins in cargo center-of-gravity operating envelope. Operations should adopt paperless management and electronic launch readiness review. Operations should be designed to select standard flight plan to convert payload properties, vehicle lift capacity, and orbital inclination, to program software, autopilot, and trajectory profile. It should validate checking the system rather than every element procedure.

VII. CONCLUSION

The purpose of this study was to seek a quality design analysis approach in support of NASA's expressed commitment[24] to make space efforts more affordable. Adapting TQM techniques to design analysis at systems inceptions was a challenge to that commitment. Since existing TQM applications were identified through all systems design phases of a payload delivery system, it should be expected to be applicable to most future aerospace systems products and operations for lowest life-cycle cost.

The basis of this study was the three-phase, systems-design analysis approach consisting of: vehicle systems concepts to satisfy user requirements; vehicle systems, elements, and components definitions to satisfy vehicle systems requirements; and detailed systems design analysis. Design analysis emphasis was on user satisfaction at least cost. The quality leverage principle asserts that backtracking costs increase as design progresses downstream. Common causes for backtracking are incomplete analysis, design deficiencies, and cost overruns.

Matrices were introduced to orderly identify and format interacting design parameters with systems, elements, and components, and particularly to support completeness of analyses. Steward's matrix process provided task ordering, information flow, and the accountability, visibility, and traceability of evolving requirements leading to solutions, interactions, and iterations. Cost, reliability, and weight were noted to be common controlling characteristics on all flight systems hardware, and suggest status tallying tasks throughout the project development.

Many existing TQM techniques were reviewed and adapted throughout the systems process with concurrent engineering being the most forceful forum to drive quality performance and reliability at least life-cycle cost. The success of team effort depends on its experience in manufacturing, operations, costs, reliability, and all other related engineering disciplines, and on its continuous

engagement from concept to detail design. The technical success of the project depends on the leadership technical experience, breadth of disciplines, and ability to bubble-up all technical conflicts and issues.

Akao's QFD technique was noted to identify user demands suggest approaches for "how" and "how much" to satisfy them. Phadke's robust methods are most effective for identifying and quantifying design parameters and combinations that will provide ideal performance at least cost. QFD techniques suggest how to manufacture it, establish level of achievement and quality check points, and how to plan for engineering bottlenecks.

It was noted that cost overruns may be avoided by controlling user requirements buildup, completing each design analysis at highest quality leverage, employing only modest technology, and not designing to edge of existing technology.

Pivotal to the launch vehicle systems are the trades and selection of propellant systems with respect to: payload performance to orbit; size, integration complexity, and reliability of engine clusters; operations processing, checkout, health monitoring, skills, and manpower. Propellant system is one of the earliest critical selections, and because it is so dominant over all other vehicle systems, its compatibility and balance with other evolving systems information must be resolved at the highest tenable quality leverage point.

Low cost, reliable operations must be intentionally designed into the delivery systems up front, and resources and time to accommodate them provided. Facilities must be flexible and expandable to serve a variety of future launch vehicles and payload requirements. They should be more automated to reduce manpower and human errors while decreasing turnaround time.

A variety of existing TQM techniques explored have prominent and multiple roles in the total systems design analyses to identify and satisfy user demands with high reliability at low cost. With some innovation, the best elements of these techniques may be combined and tailored for more versatile applications and better results. More and improved TQM techniques are evolving, and more analysts are being trained. Project management should expect maximum practical use of TQM, should support it up front, and should critically review it throughout the systems process to better afford NASA's space strategy.

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As emphasis shifts from optimum-performance aerospace systems to least life-cycle costs, systems designs must seek, adapt, and innovate cost improvement techniques in design through operations. The systems design process of concept, definition, and design was assessed for the types and flow of total quality management techniques that may be applicable in a launch vehicle systems design analysis. Techniques discussed are task ordering, quality leverage, concurrent engineering, Pareto's principle, robustness, quality function deployment, criteria, and others. These cost oriented techniques are as applicable to aerospace systems design analysis as to any large commercial system.

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